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Single-mode optical fibre linkages of large telescopes at visible wavelengths: experimental results

S R Restaino†, J Baker‡, R A Carreras†, J L Fender†, G C Loos†, R J McBroom‡, D Nahrstedt§ and D M Payne‖

† USAF/Phillips Laboratory/LIM, 35550 Aberdeen SE KAFB, NM 87117, USA
‡ Rockwell Power Systems, PO Box 6060 KAFB, NM 87117, USA
§ Rocketdyne Division, Rockwell International Corporation, 6633 Canoga Avenue, Canoga Park, CA 91303, USA
‖ W J Shafer Assoc, Inc, 2000 Randolph Road, SE Albuquerque, NM 87106, USA

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Abstract. In this paper we present results of an experiment in which the link between two 1.2 m telescopes was obtained using single-mode optical fibres with polarization-preserving cores. An additional novelty of this experiment is the use of a tipping–tilting stabilization system on each telescope. We present results for the measured coupling efficiency with and without tip/tilt stabilization. Furthermore, we present white-light fringe-visibility measurements obtained on light from the star Alpha Bootis.

1. Introduction

The manufacture of large conventional astronomical telescopes is currently limited to the size range of 8–10 m. There is an emerging interest in the use of optical interferometry to synthesize apertures larger than those which can be realized using current mirror-fabrication technologies. The use of single-mode (SM) optical fibres as light conduits has been suggested by several authors. The reason resides in the perfect spatial coherence characteristics of such fibres, in addition to the powerless transport of the signal. However, the extremely low light-coupling efficiency between the *seeing* degraded image from the telescope and the fibre has been a major practical issue in experimental attempts to link two large telescopes, namely those with diameters larger than the atmospheric coherence diameter r_0, especially at visible wavelengths.

The idea of using SM optical fibres for optical interferometry has been suggested by several authors [1, 2]. We will review the most important characteristics of SM fibres and their application to optical interferometry. As their name suggests, SM fibres can carry only one spatial mode, making them, in effect, ideal spatial filters. In the case of a wavefront corrupted by atmospheric turbulence this results in the aberrated energy being filtered out, leaving only a very *clean* wavefront. This is extremely important for interferometric beam recombination since in this case only two coherent wavefronts will correlate to give rise to a fringe pattern. Additional attractive characteristics of SM fibres include the basically lossless power transportation and the possibility of relaying beams for several meters without the necessity of extremely accurate optical alignments. Finally, there is the possibility of achieving optical path difference (OPD) compensation in SM fibres. Sub-millimetric OPD adjustment has been demonstrated in [3] and details of a sub-metric elastic fibre delay line were published in [4]; finally, the theoretical extension of such a technique was suggested in [5]. Of course, such a technique is very attractive for its economy and simplicity. However, there is a major drawback to using SM fibres (in fact up to now only theoretical suggestions have been made and very little experimental work). The drawback is the coupling efficiency, namely the ratio between the total energy collected by the telescope and the amount of energy injected into the fibre. Although the theoretical limit for a well-focused beam is of the order of 80%, when atmospheric degradation is taken into account an extreme drop in coupling efficiency results. Later in the paper we will give an approximate expression for the coupling efficiency of an atmospherically corrupted spot with or without tilting removed. For now, it is sufficient to state that, under average seeing conditions, D/r_0 of the order of 10, the coupling efficiency is of the order of 1%. However, the potential benefits of using SM fibres are still such that it is important to investigate their use experimentally.

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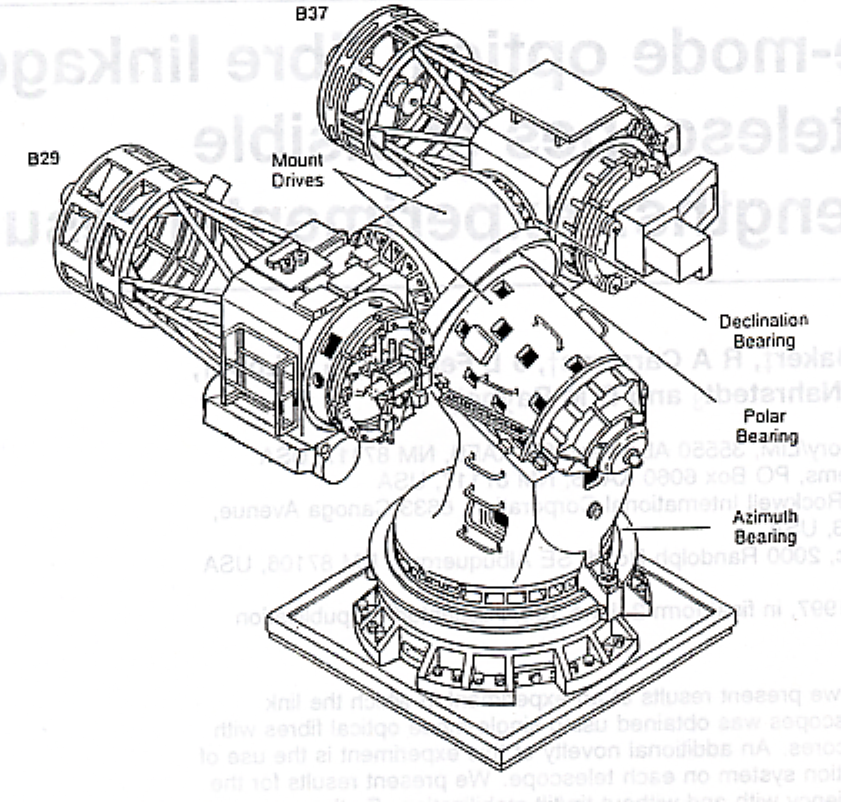


Figure 1. The Maui Optical Tracking and Identification Facility (MOTIF) telescope.

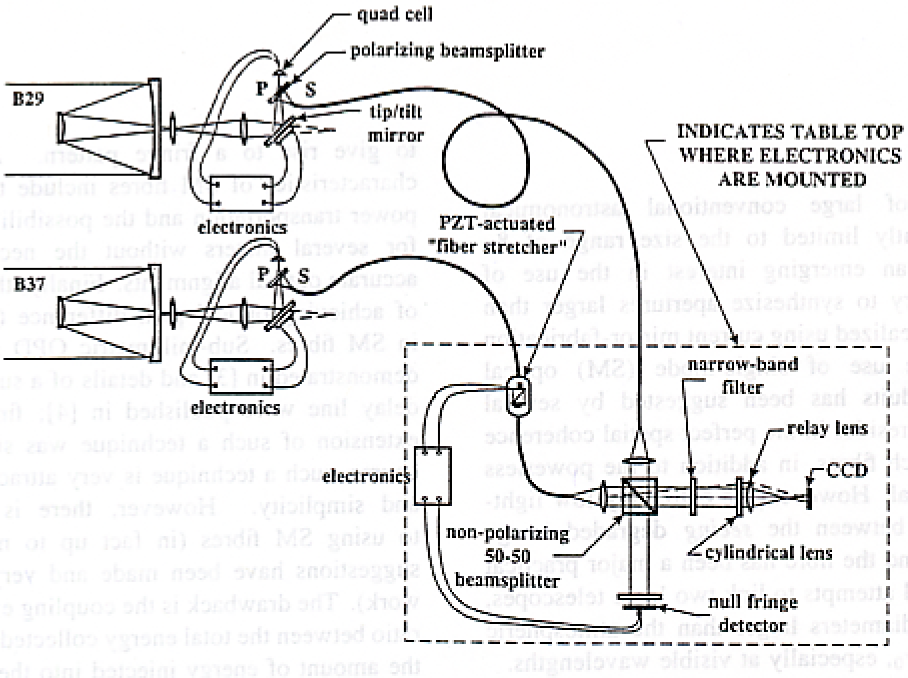


Figure 2. A schematic diagram of the optical lay-out of the experiment.

In section 2 of this paper we present the experimental set-up and the data-acquisition scheme. Section 3 deals with the efficiency of the coupling between the telescopes and the fibres with and without wavefront tipping–tilting removed. Finally, section 4 reports the data analysis and results for the fringe visibility of the white-light fringes obtained from the stellar object.

2. The experimental set-up

The experiment described in this paper took place in two steps during the periods February 1995 and June 1995 at the Maui Space Surveillance Site (MSSS), a USA Air Force facility located atop Mount Haleakala in Maui, Hawaii. At this location the Air Force Space Command

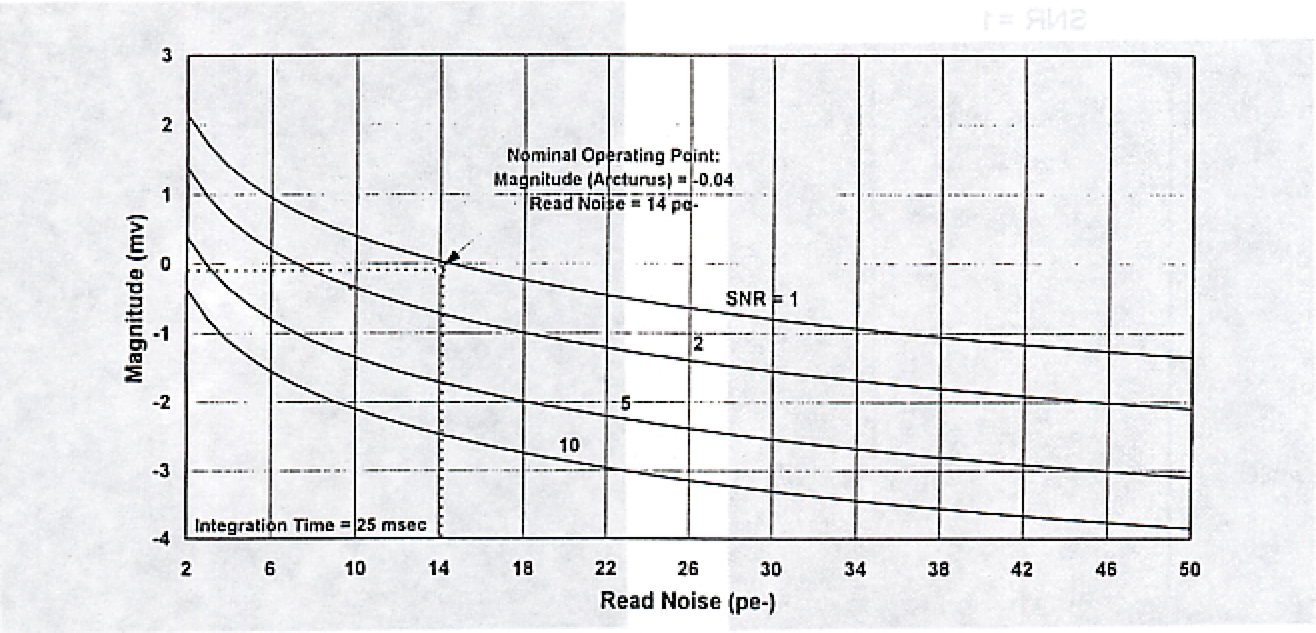


Figure 3. A plot of the limiting magnitude versus the CCD read-noise for four different SNR levels.

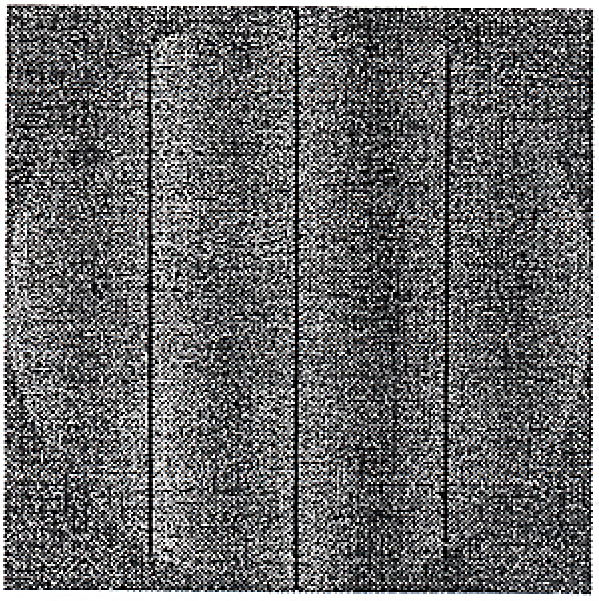
Table 1. The experimental parameters and major optical components.

Optics	Electronics
B29 telescope *F* number 20 and B37 telescope *F* number 16	Maximum allowable bandwidth for tipping–tilting mirrors 500 Hz (closed loop)
Newport fibres	Bandwidth of piezoelectric stretcher 1 KHz.
Spectral filter: 100 nm FWHM centred at 800 nm	CCD camera: Kodak chip (768×512 pixels), using a window of 128×64 pixels
Tipping–tilting mirrors of 1″ diameter	Hamamatsu R636 photomultiplier
Cylindrical lens $f = -300$ mm	GE low-light camera

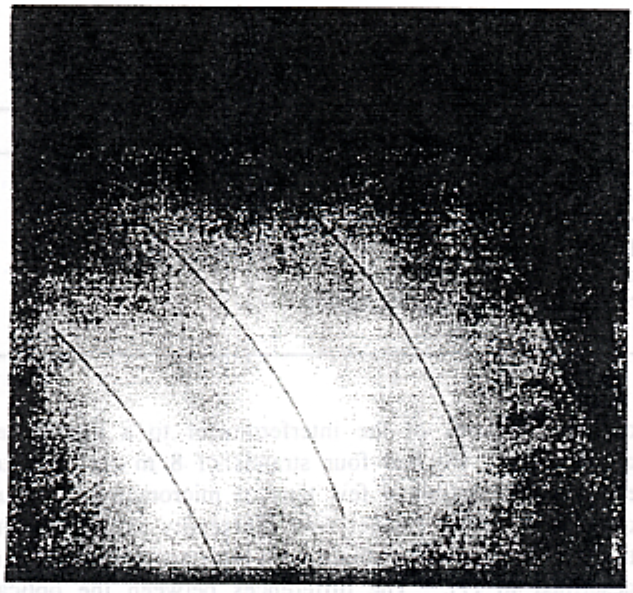
maintains a unique facility, the Maui Optical Tracking and Identification Facility (MOTIF) telescope.

This facility is composed of two 1.2 m telescopes co-mounted in a binocular-type arrangement (see figure 1). The two telescopes are not identical and the relay optics to the SM fibres must be different in order to achieve the same *F* number for both fibres. Figure 2 is a schematic diagram of the optical lay-out of the experiment. The main parameters of the experiment are listed in table 1.

We had three main sub-systems. The first was the fast steering mirrors that stabilized the image at the end of the fibres. A detailed description of these systems is to be found in [6] and table 1 lists the main parameters of interest here for the experiment. The second sub-system included the relay optics, the optical fibres and the strain-compensation system. Finally there were the acquisition systems; the first system, based on a CCD camera, was the fringe-acquisition system; the second, based on a photo-multiplier tube (PMT), was the fringe-tracking system. This last channel could be used either for the fringe-tracking system or, by exchanging the PMT for a low-light camera, as an on-line alignment system. In dealing with broad band light, dispersion becomes an important consideration [7]. The broader the spectrum the more pronounced the decrease in visibility due to the dispersion [7, 8]. In order to maintain high fringe visibility in broad-band use it is necessary to balance the path length of the two arms of the interferometer to a high level of accuracy. We had four strands of 8 m each cut to equal length, within a few tens of micrometres, by our colleagues at the Herriot-Watt University in Edinburgh; the procedure used to obtain such high accuracy has been described in [7]. The differences between the optical lengths of the fibres were checked interferometrically using a Michelson interferometer, by splicing the fibres on to a well-balanced fibre coupler. We followed the Herriot-Watt technique for such measurements. One arm of the coupler was stretched until the broad-band interferogram became visible. The cut lengths of fibre were then heated to observe a fringe pattern, verifying that the fringes were due to the overall Michelson interferometer, rather than to vestigial reflections at the spliced ends of the coupler arms. The measurements for the two strands used during the experiment were $L_1 - L_2 + \Delta = -19$ μm, where L_i is the length of fibre i, Δ is the length imbalance of the directional coupler and all lengths represent the amount by which the coupler arm must be stretched to balance the group delay. This is not the same as the physical difference in length, but it is a close approximation thereto. The estimated measurement error was 5 μm. Broad-band interferograms, estimated to be in the range 0.5–1 μm, exhibited significant dispersion with an arc lamp; however, no measurements to quantify the dispersion were performed. The normalized birefringence is defined as $B = \delta\beta/\beta$, where $\delta\beta$ is the



(a)



(b)

Figure 4. A comparison between (a) the calculated fringe pattern for a SNR of unity and (b) a sample of observed fringes.

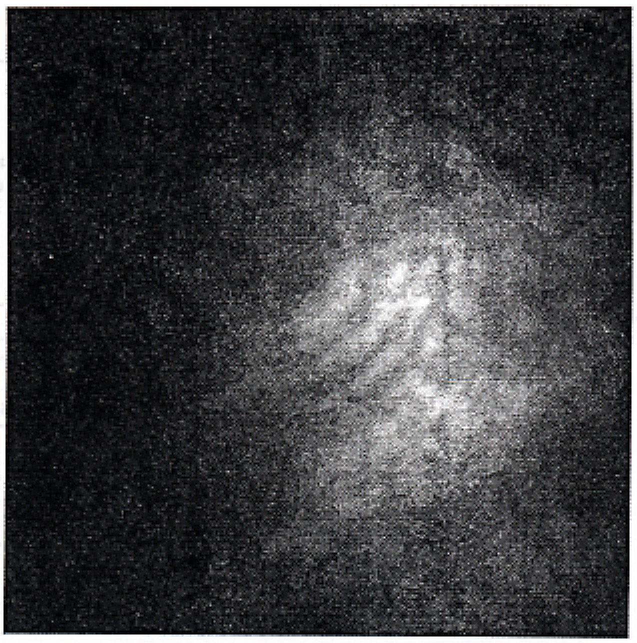


Figure 5. A typical raw frame from the 16 June observing run.

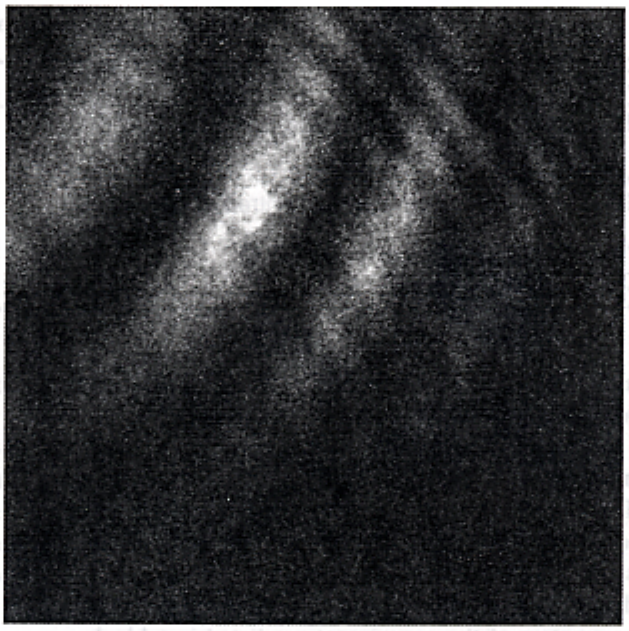


Figure 6. The same frame as in figure 5, but with the average intensity background subtracted.

difference between the propagation constants along the two axes of the elliptical core and β is the average of the two propagation constants. For our fibres the normalized birefringence was 1.5×10^{-4}.

We also decided to limit the bandpass of the light by using a spectral filter centred at 800 nm with a FWHM of 150 nm. This last precaution became necessary when, during the mounting of one of the fibres we broke the tip off. It was necessary to re-cleave both strands of fibres, the final accuracy being within the order of about 100 μm.

2.1. Optical lay-out considerations

As shown in figure 2 the relay optics from the two telescopes to the SM fibres was chosen in order to obtain an F number equal to 5 for both systems. This choice was based on a suggestion made by Shacklan and Roddier [2], as well as on rough estimates of the spot size obtainable by use of such a system. We used typical values of the atmospheric coherence diameter, r_0, as measured at the MSSS. For the expected spot diameter we performed some photometric calculations and obtained an expected coupling efficiency of approximately 1%. This value is in close accordance with the more correct estimation derived from the coupled modes and the Kolmogorov theory of atmospheric turbulence, as described in the next section. We used polarization-preserving fibres (see table 1) and polarizing beam-splitters to send one polarization state into the fibre and the other into the quad-cell detector for the fast steering mirrors. We had a final cylindrical lens as the re-imaging lens for the CCD camera with the goal of

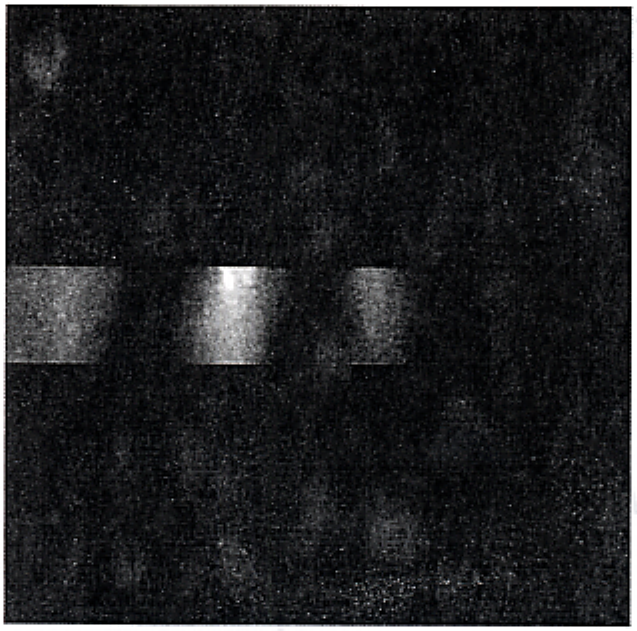


Figure 7. The same frame as figures 5 and 6, but with the filter applied and averaged within a window of 128 × 20 pixels.

increasing the throughput in one direction. The theoretical throughput computed was 1.25%, which was well matched by the 1.1 ± 0.1% measured during the coupling-efficiency measurements. The throughput was measured using the alignment laser diode.

Owing to the overall poor throughput of the system, only fairly bright objects could be targetted in this first version of the experiment, which was intended merely to provide proof of the validity of the concept. The selected object during the final, successful, run in June was α Bootis, in Arcturus.

The results of the photometric model are shown in figures 3 and 4. In figure 3 is shown the relationship between the visible magnitude and the camera read-out noise. Four different signal-to-noise ratio (SNR) values were plotted and the 'operating' point was noted. In figure 4 is shown a comparison of the fringe contrast calculated with a SNR of unity and the observed fringe contrast.

Finally, we had two levels of optical path difference (OPD) adjustment. The first was in air using a motor mount for the B29 fibre arm, see figure 2. The second was into the fibre with the piezoelectric stretcher onto which the B37 fibre arm was wound. This second, fast, system was able to attain a 1 kHz bandwidth with approximately 6 μm of overall dynamic range.

3. Coupling-efficiency measurements

One of the aims of the experiment was to measure the efficiency of the coupling between a large telescope ($D \gg r_0$) and a single-mode fibre. The choice of a large telescope was dictated by the need to verify the efficiency of the coupling between SM fibres and an atmospherically corrupted image. The coupling efficiency is defined as the ratio of the total energy focused by the telescope to the amount of energy injected into the fibre. We performed an extensive photometric analysis, the results of which were in agreement with the experimental data. In table 2 are shown the parameters used for the photometric analysis of the coupling efficiency. We measured the efficiency with and without tipping–tilting removed and compared the results with an asymptotic expression [10]:

Table 2. The photometric parameters used for the analysis of the coupling efficiency.

Component	Transmission (%)
Atmosphere	80
Optics	22
Detector	QE 80

$$\eta \approx \left(\frac{r_0}{D}\right)^2 \left[1 + 1.06\mu \left(\frac{r_0}{D}\right)^{1/3} + 1.24\mu \left(\frac{r_0}{D}\right)^{2/3}\right] \quad (1)$$

where the parameter μ is equal to unity if the tilting has been removed and to zero without removal of tilting. For r_0 we used an average of the values measured on the compensated imaging system (CIS) installed on a 1.6 m telescope located approximately 20 m away from the MOTIF dome. The value used was $r_0 = 13$ cm. With this value in equation (1) we obtained estimated coupling efficiencies of 1.1% and 2.1% respectively without and with tilting removed. The experimentally measured values were, respectively, 0.9% and 3% with standard deviations for the two measurements of $\sigma_{tilt} = 0.18$ and $\sigma_{notilt} = 0.2$, respectively. The subscripts tilt and notilt refer to the tilting correction and non-correction, respectively. The discrepancy with the tilting-removed coupling efficiency may have been due to two different causes. Our average r_0 value may be wrong; however, the agreement without tilting removed speaks against this possibility. The coupling efficiency without tilting removal is basically a measurement of r_0/D and, within the limitation of experimental error, we believe that the value of r_0 is accurate enough. The second possibility could have arisen from the fact that equation (1) was derived using Kolmogorov statistics for the global tilting. It may well be that, under conditions of good visibility, this assumption is not valid and some experimental data [11] seem to suggest that such a hypothesis may be correct.

4. The reduction of the data

In total 100 data frames were collected during the night of 16 June 1995. The exposure time per frame was 25 ms and we had two sets of 50 frames each separated by 15 min approximately. In figure 5 is shown a raw frame acquired during the observing run. In figure 6 is shown the same frame after the average intensity has been subtracted. The curvature in the fringes was due to a certain amount of defocus introduced by motion of one of the re-imaging lenses. Figure 7 shows the final data after filter had been applied to remove residual rings that the flat-fielding process was not able to remove and a window of 128 × 20 pixels was chosen to average the fringes in order to increase the SNR.

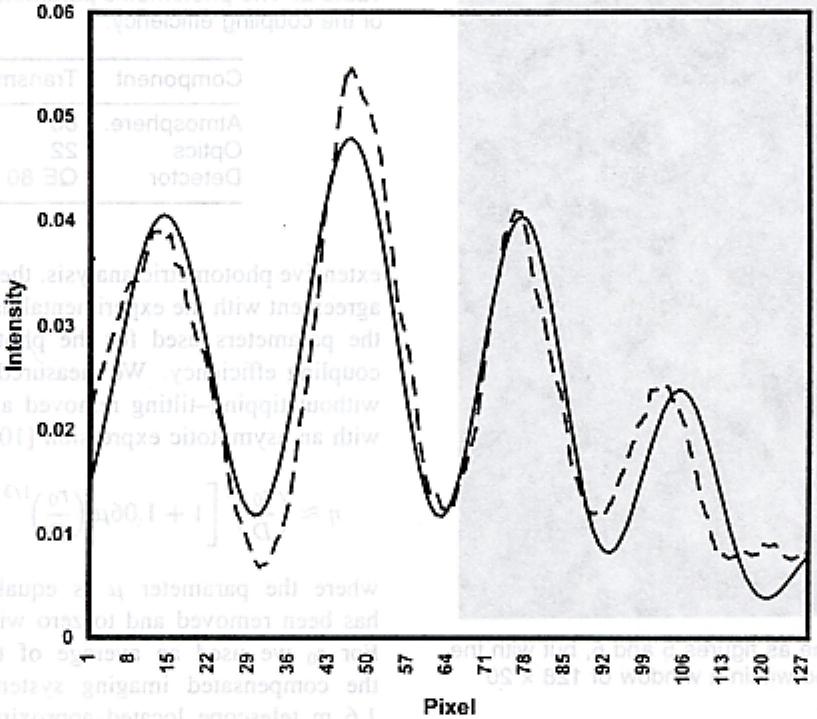


Figure 8. A plot of the cross section of the fringe pattern of the frame shown in figures 5–7 (full curve) compared with the least-squares fit result (broken curve).

Table 3. Results from the three different techniques for measuring the fringe visibility.

Michelson method		Fourier transform		Least-squares fitting	
Average	σ	Average	σ	Average	σ
0.512	0.132	0.415	0.048	0.367	0.115

We decided to use three different techniques to measure the fringe visibility from the data. The first technique was the classical Michelson definition.

The second technique consisted of using Fourier-transform techniques. Finally, the third technique used was a least-squares fitting of the analytical expression for the fringes, namely

$$V = 2\left(\frac{1}{\sigma(2\pi)^{1/2}}\right)^2 \{\exp[-(\rho_f-\alpha)^2/(2\sigma^2)]\}^2 \times\left[1+\mu\cos\left(\frac{2\pi}{\lambda f}(\xi x+\eta y)\alpha\right)\right] \qquad (2)$$

where $\rho_f = \pi/[(\lambda f)\rho]$. The presence of the Gaussian function is due to the characteristic mode shape of the mode coupled into the fibres.

As pointed out before, during the normal operation of the telescope one of the re-focusing lenses in the recombination beam system moved. The result was that one of the beams was slightly de-focused relative to the other. The least-squares fit worked best when, instead of one Gaussian function, we used two, leaving the width and the peak amplitude of the functions as free parameters. This seems to indicate a sensitivity to the measured data, according to the least-squares techniques, not exhibited by the other two. The natural behaviour of the three different techniques was also demonstrated by the fact that the Michelson method tended to over-estimate the fringe visibility, whereas the Fourier-transform method, that we had assumed to be less biased, and the least-squares approach, instead, tended to under-estimate the visibility. The average fringe visibilities measured with the three techniques are reported in table 3 with the respective standard deviations. It should be noted also that we had no way of recording the position of the OPD scanner precisely, so we had no precise measure of the zero OPD position. This resulted in a loss of fringe visibility.

5. Conclusions

We have reported the first controlled link between two independent telescopes at visible wavelengths using SM fibres concerning light from a real star. The use of single-mode fibres can reduce the cost of ground-based optical interferometers dramatically and has the potential for even larger savings with spaced-based ones. The possibility of building optical interferometers, the optical equivalents of the large radio interferometers like the VLA, will open a completely new chapter in the field of astronomy and visible imaging. We have presented also the first experimental measurement of an increase in coupling efficiency using the removal of tipping–tilting to stabilize the image onto the fibre core. The analytical expression compared well with the experimental data in the case without removal of tipping–tilting but there was a discrepancy when the image was stabilized. This finding requires further analysis. Furthermore, we have presented a comparison among three different techniques for measuring the fringe visibility. Although the three different techniques generally compared very well, the sensitivity of the least-squares method to some of the experimental parameters may have resulted in a powerful means of estimating fringe visibilities under less than perfect experimental conditions.

Acknowledgments

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